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## Research Article

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Palmer amaranth; *Amaranthus palmeri* S. Wats.; waterhemp; *Amaranthus tuberculatus* (Moq) Sauer; cereal rye; *Secale cereale* L.; soybean; *Glycine max* (L.) Merr.

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# Effects of cereal rye seeding rate on waterhemp (*Amaranthus tuberculatus*) emergence and soybean growth and yield

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### Abstract

The evolution of herbicide-resistant weeds has resulted in the necessity to integrate nonchemical control methods with chemicals for effective management in crop production systems. In soybean, control of the pigweed species, particularly herbicide-resistant waterhemp and Palmer amaranth, have become predominant concerns. Cereal rye planted as a winter cover crop can effectively suppress early-season weed emergence in soybean, including waterhemp, when planted at a rate of 123 kg ha$^{-1}$. The objectives of this study were to determine the effects of different cereal rye seeding rates (0, 34, 56, 79, 110, and 123 kg ha$^{-1}$) on early-season waterhemp suppression and soybean growth and yield. Soybean was planted into fall-seeded cereal rye, which was terminated within 4 d of soybean planting. The experiment was conducted over the 2018, 2019, and 2020 growing seasons in Columbia, Missouri. Effects of cereal rye on early-season waterhemp suppression varied by year and were most consistent at 56 kg ha$^{-1}$ or higher seeding rates. Linear regression analysis of cereal rye biomass, height, or stand at soybean planting showed inverse relationships with waterhemp emergence. No adverse effects on soybean growth or yield were observed at any of the cereal rye seeding rates relative to plots that lacked cereal rye cover. Result differences among the years suggest that the successfulness of cereal rye on suppression of early-season waterhemp emergence is likely influenced by the amount of waterhemp seed present in the soil seed bank.

## Introduction

Increased incidences of herbicide-resistant weed species and public concern over reducing anthropogenic inputs in agriculture have generated renewed interests in incorporation of cover crops in the United States row crop production systems (Hand et al. 2019; Wittwer 2017). According to the 2017 National Agriculture Census data, cover crops were planted on 6.2 million hectares, with highest adoption occurring in the mid-Atlantic region (Zuluaf and Brown 2019). Benefits of incorporating cover crops into a cash cropping system include prevention of soil erosion and nutrient leaching; increases in soil microbial abundance, activity, and diversity; carbon sequestration; and weed suppression (Cornelius and Bradley 2017; Kim et al. 2020; Poeplau and Don 2015; Thapa et al. 2018). Because of these ecological benefits the U.S. Department of Agriculture–Natural Resources Conservation Service (USDA-NRCS) offers multiple incentive programs for producers to plant cover crops (USDA-NRCS 2018).

Cover crops can suppress weed growth through physical and chemical means. The generated biomass can create mat-like physical barriers, which obstruct the growth of emerging seedlings (Teasdale and Moehler 2000). Certain cover crops, such as cereal rye (*Secale cereale*), can exude chemicals that have allelopathic effects and inhibit germination of specific weed species (Barnes and Putnam 1986; Burgos et al. 1999).

Cash crop production losses are estimated to be as high as $33 billion annually due to weed interference (Pimentel et al. 2005). Herbicide-resistance incidences continue to increase and reduce viable chemical options for weed control. In soybean production systems, control of the pigweed species, particularly waterhemp and Palmer amaranth, have become predominant concerns. A waterhemp population in Missouri was confirmed resistant to six herbicide sites of action (SOAs Shergill et al. 2018). More recently in Illinois, a waterhemp population was confirmed to be resistant to five herbicide SOAs, including the synthetic auxin herbicide 2,4-D, to which the waterhemp population had not been exposed (Evans et al. 2019). A Palmer amaranth population from Kansas was also recently confirmed to have resistance to five SOAs (Kumar et al. 2019). Prior to 2020, incidences of Palmer amaranth or waterhemp evolving resistance was mostly limited to POST herbicides. However, in 2020, two waterhemp populations resistance to S-metolachlor were confirmed (Strom et al. 2020). S-metolachlor is categorized by the Weed Science Society of America as a Group 15 herbicide that provides residual activity and prevents or delays emergence of waterhemp.

Cereal rye has been shown to effectively suppress early-season weed emergence in cash crops, especially small-seeded broadleaf weeds such as waterhemp and Palmer amaranth, which depend on light for germination (Cornelius and Bradley 2017; Hand et al. 2019; Teasdale 1996). Cornelius and Bradley (2017) found that out of nine cover crop species or mixes tested, cereal rye was the only fall-seeded cover crop to suppress early-season waterhemp emergence in soybean in Missouri at a comparable level to a PRE residual herbicide program. Hand et al. (2019) found that roller crimped cereal rye could suppress early-season Palmer amaranth emergence in cotton (*Gossypium hirsutum* L.) to similar levels as a thorough broadcast herbicide program in Georgia. More recently, Schramski et al. (2020a) found that in Michigan, planting a cash crop directly into nonterminated (green) cereal rye and winter wheat [*Triticum aestivum* L.] reduced early-season glyphosate-resistant horseweed [*Conyza canadensis* (L.) Cronq.] biomass more consistently than when the winter cereal cover crop was terminated prior to planting. The plots that were planted into nonterminated cover crops also resulted in 46% to 93% more glyphosate-resistant horseweed control than plots with no cover crop (Schramski et al. 2020a). These results indicate that producers can use cereal rye as a nonchemical option to integrate into the weed management system for early-season suppression of summer annual weeds in row crop production systems.

One caveat of the weed suppression research is that producers must use specific cover crop seeding rates to qualify for USDA-NRCS incentive programs. These seeding rates vary across climate and state (USDA-NRCS 2012, 2018). In the previously-mentioned studies on weed control with cereal rye, Cornelius and Bradley (2017) seeded cereal rye at 123 kg ha$^{-1}$; Hand et al. (2019) seeded at 100 kg ha$^{-1}$; and Schramski et al. (2020a,b) seeded at 67 kg ha$^{-1}$. Approved USDA-NRCS seeding rates for drilled or broadcasting cereal rye in Missouri are 44.8 kg ha$^{-1}$ and 56.0 kg ha$^{-1}$, respectively, whereas rates in Georgia are less specific, ranging from 62 to 126 kg ha$^{-1}$ (USDA-NRCS 2015). Recommended rates in Michigan are 31.3 to 125.5 kg ha$^{-1}$ (USDA-NRCS-MICH 2013). Therefore, research is needed to determine effect of cereal rye seeding rate on weed suppression and soybean yield.

The objectives of this study were to 1) characterize waterhemp emergence and soybean growth and yield across multiple cereal rye seeding rates when soybean was planted into a nonterminated, living stand of cereal rye; 2) identify optimal cereal rye seeding rate(s) to maximize waterhemp suppression in a plant-green system; and 3) quantify relationships between cereal rye biomass and waterhemp emergence.

## Materials and Methods

### Site Location and Design Description

Field experiments were conducted in 2018, 2019, and 2020 at the University of Missouri Bradford Research Center near Columbia, MO. Cereal rye was planted in rows spaced 19 cm apart at a depth of 1.9 cm and at rates of 0, 34, 56, 78, 110, and 123 kg ha$^{-1}$ on October 26, 2017; October 25, 2018; and November 5, 2019. Experimental design for the cereal rye seeding rate treatments was a randomized complete block. Individual plots were 3 × 27 m, and each seeding rate was replicated six times per experiment. Different experimental sites were selected each year at the research center; therefore, pH and organic matter varied slightly by year. Soil pH was 6.3 and organic matter 2.5% at the 2017 planting site; 5.5 and 2.2%, respectively, at the 2018 site; and 5.7 and 2.3%, respectively, at the 2019 site. Soybeans were planted at 407,000 seeds ha$^{-1}$ in 76-cm rows and at a depth of 1.9 cm on May 16, 2018; May 17, 2019; and May 25, 2020. Prior to soybean planting, bareground plots were treated with 1.27 kg ha$^{-1}$ glyphosate. Following soybean planting, the cereal rye was terminated with 1.27 kg ha$^{-1}$ glyphosate on May 17, 2018; May 20, 2019; and May 29, 2020. Bareground plots were also treated at cereal rye termination. No additional weed control measures were taken during the course of the study.

### Data Collection and Analysis

Cereal rye stand, height, and stage were recorded at soybean planting. Cereal rye stages were recorded using the Zadoks growth scale at soybean planting in 2019 and 2020 (Zadoks et al. 1974). Cereal rye biomass was measured by harvesting the aboveground tissues using two 0.33 m$^{-2}$ quadrats per plot and recording fresh weights. Soybean stand and height were evaluated 14 d after planting (DAP). Stand was measured in 1 m of row, and the average height of those plants was recorded. Waterhemp control was assessed by visual ratings of emergence 28 DAP on a percentage scale with 0% meaning emergence equal to plots that lacked cover crop and 100% meaning no waterhemp emergence. Waterhemp density was measured at 14, 28, and 42 DAP by counting plants. Two counts were conducted in each plot using 0.5 m$^{-2}$ (2018 and 2020) or 0.33 m$^{-2}$ (2019) quadrats. After each count, waterhemp seedlings that were not pulled at the time of counting were controlled by an application of glufosinate over the entire plot so that only newly emerged weeds were recorded at each count interval. Air temperature and precipitation data referenced in the Results and Discussion (Table 1) were retrieved from the University of Missouri Historical Agricultural Weather Database (http://agebb.missouri.edu/weather/history/index.asp). Growing degree days for cereal rye were calculated using a base temperature of 4.4 C (Schramski et al. 2020b).

Data were subjected to analysis using SAS version 9.4 (SAS Institute, Cary, NC). The UNIVARIATE procedure was used to test for normal distribution. Data were log or square root transformed, depending on which transformation resulted in normalization. Data were then subjected to the GLIMMIX procedure to determine differences among least squares means. Dependent variables were cumulative waterhemp emergence for 14, 28, and 42 DAP; waterhemp ratings 28 DAP; soybean stand and height 14 DAP; cereal rye stand; height and biomass at soybean planting; and soybean yield at harvest. Cereal rye seeding rate, year, and their interactions were considered fixed effects. Individual treatment differences were separated using Fisher's protected LSD test at $P \leq 0.05$. The REG procedure in SAS was used to generate regression models with waterhemp emergence as the dependent variable and cereal rye biomass as the independent variable. Data were graphed using R software version 3.5.2 "Eggshell Igloo" (R Core Team 2020).

## Results and Discussion

### Cereal Rye Growth and Biomass

There was an interaction between cereal rye seeding rate and cereal rye stand (Figure 1A). For the lowest seeding rate of 34 kg ha$^{-1}$, there were 49 cereal rye plants per square meter. At the highest

**Table 1.** Monthly and 10-yr average precipitation and air temperatures at the research location.

| | Precipitation[a] | | | | Average air temperature | | | |
|---|---|---|---|---|---|---|---|---|
| | 2018 | 2019 | 2020 | 10-yr average | 2018 | 2019 | 2020 | 10-yr average |
| | mm | | | | C | | | |
| Fall and winter[b] | 127 | 254 | 231 | 192 | 1.4 | 0.5 | 1.4 | 1.4 |
| March | 147 | 93 | 134 | 72 | -4.8 | 3.8 | 8.0 | 6.9 |
| April | 10 | 101 | 107 | 125 | 8.3 | 12.9 | 10.5 | 12.7 |
| May[c] | 71 | 113 | 89 | 108 | 21.9 | 17.3 | 15.8 | 18.1 |
| June | 114 | 154 | 156 | 98 | 24.5 | 21.5 | 22.9 | 23.4 |
| July | 64 | 96 | 94 | 94 | 24.3 | 24.3 | 24.8 | 25.0 |

[a]Missouri Automated Weather Network (mesonet.missouri.edu).
[b]Weather data collected from fall planting of cereal rye cover crop through the end of February.
[c]Waterhemp emergence was counted from 14 DAP (days after soybean planting) on May 16, 2018; May 17, 2019; and May 25, 2020, respectively, to 42 DAP.

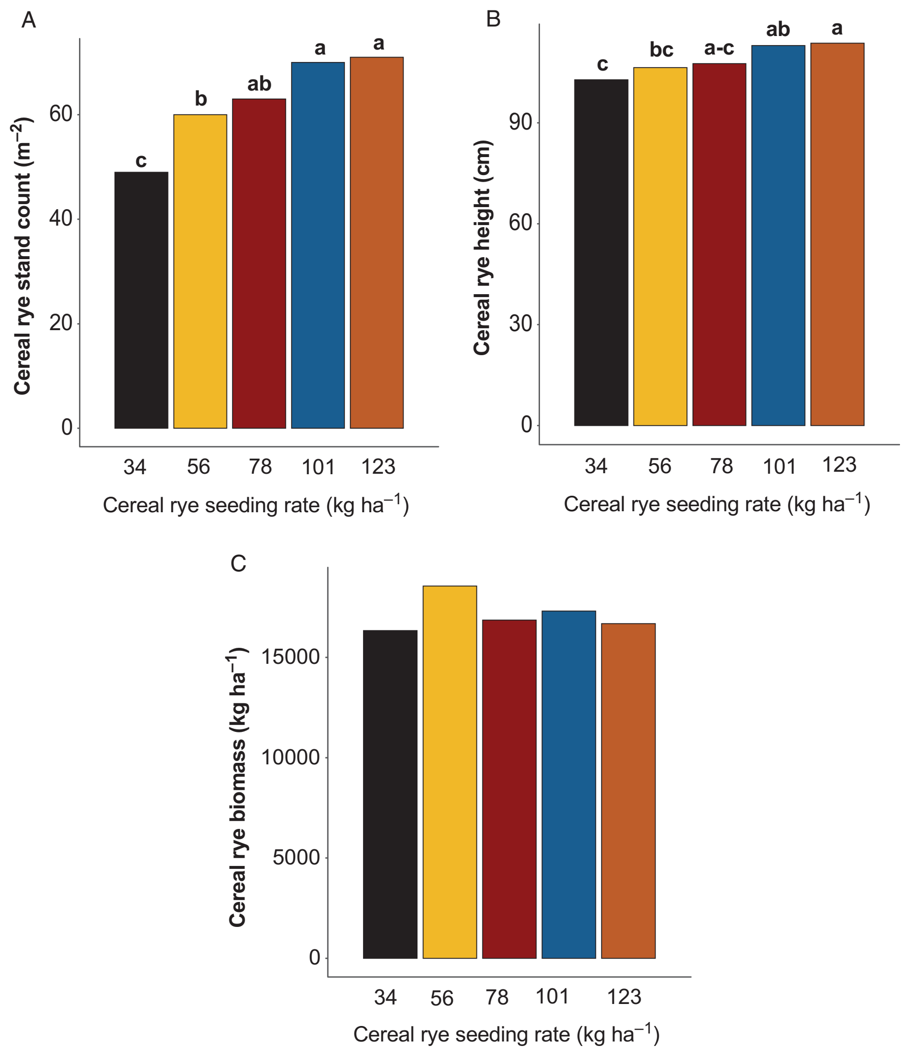


**Figure 1.** Influence of cereal rye seeding rates on cereal rye stand counts (A), height (B), and biomass at time of soybean planting (C). Significance values were $P < 0.01$, $<0.01$, and 0.22, respectively. Data summarized across years (2018, 2019, 2020) in Columbia, MO.

seeding rate of 123 kg ha$^{-1}$, stands were 71 plants per square meter, and this was similar to seeding rates of 78 and 101 kg ha$^{-1}$, respectively.

An interaction was observed between cereal rye seeding rate and height. Cereal rye seeded at the lowest rate of 34 kg ha$^{-1}$ corresponded to the shortest plants, which were 103 cm at soybean planting. The highest cereal rye seeding rate of 123 kg ha$^{-1}$ corresponded to the tallest plants at 114 cm. Cereal rye seeded at 78 and 101 kg ha$^{-1}$ had heights similar to the highest seeding rate of 123 kg ha$^{-1}$ (Figure 1B). Observed height differences are likely due to competition among cereal rye plants growing in the higher seeding rate plots, which grew in closer proximity than those at lower seeding rates.

There was an interaction between cereal rye seeding rate and cereal rye maturity at soybean planting, although differences between treatments were subtle. The Zadoks stage was 60 (flowering) for the

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**Table 2.** Cereal rye and soybean stand, heights, and yield averaged over cereal rye seeding rates.

| Year | Cereal rye[a] | | | Soybean[b] | | |
|---|---|---|---|---|---|---|
| | Stand[c] | Height | Biomass | Stand | Height | Yield |
| | plants $m^{-2}$ | cm | kg $ha^{-1}$ | per m row | cm | kg $ha^{-1}$ |
| 2018 | 76 a | 76 c | 15,390 b | 19 c | 12 | 3,110 b |
| 2019 | 48 c | 107 b | 14,010 c | 20 b | 13 | 3,720 a |
| 2020 | 64 b | 143 a | 20,410 a | 22 a | 12 | 3,660 a |
| P-value | <0.01 | <0.01 | <0.001 | <0.01 | 0.05 | <0.01 |

[a]Cereal rye was seeded at rates of 0, 34, 56, 78, 101, and 123 kg $ha^{-1}$ at the end of October or early November of 2017, 2018, and 2019 in Columbia, Missouri.
[b]Soybean were planted into non-terminated green cereal rye in May of each year.
[c]Measurements were taken at soybean planting. Means within a column followed by the same letter are not significantly different.

highest cereal rye seeding rates (101 and 123 kg $ha^{-1}$) and 59 (ear emergence complete) for the lowest cereal rye seeding rates (34 and 56 kg $ha^{-1}$; data not shown). Differences were also observed between years. Cereal rye maturity at planting in 2019 was slightly delayed relative to cereal rye in 2020 at Zadoks stages of 59 and 60, respectively (data not shown).

No interaction was observed between cereal rye seeding rate and cereal rye biomass at soybean planting (Figure 1C). Biomass ranged from 16,339 kg $ha^{-1}$ at the seeding rate of 34 kg $ha^{-1}$ to 18,557 kg $ha^{-1}$ at the seeding rate of 56 kg $ha^{-1}$. Similar results have been found in fall-seeded rye in Georgia, Illinois, Maryland, and Pennsylvania (Webster et al. 2016; Masiunas et al. 1995; Ryan et al. 2011.) The ability of cereal rye to establish tillers likely allows for more horizontal expansion of cereal rye plants at lower seeding rates compared with those planted at higher seeding rates.

Differences were observed in cereal rye stand, height, and biomass accumulation each year (Table 2). More biomass was produced in 2020 (20,410 kg $ha^{-1}$) than in 2018 (15,386 kg $ha^{-1}$) and 2019 (14,008 kg $ha^{-1}$). Cereal rye planting occurred on dates that were within the same week each year. However, soybean was planted 1 wk later in 2020, and this resulted in more cumulative growing degree days (2,732) compared with 2018 and 2019 (2,702 and 2,512 respectively). Precipitation is known to influence biomass accumulation; however, an obvious trend was not observed between cumulative precipitation and cereal rye biomass (Tables 1 and 2).

Collectively, these results indicate that in fall-planted cereal rye in Missouri, seeding rate does not necessarily affect the total amount of biomass produced, similar to results reported by Webster et al (2016); Masiunas et al. (1995) and Ryan et al (2011). In this study, cereal rye was terminated after soybean planting. It is possible there would be an effect of seeding rate on biomass if the cereal rye cover had been terminated in the weeks prior to cash crop planting.

## Soybean Growth and Yield

There was no interaction between cereal rye seeding rate and soybean stand 14 DAP (Figure 2A). Soybean per meter of soybean row ranged from 20 to 22 plants across treatments, regardless of whether the cereal rye cover crop was present or absent and regardless of seeding rate. These findings are consistent with previous research that documented a lack of relationship between cereal rye biomass and soybean stand (Nord et al. 2011).

Soybean height at 14 DAP was shorter in non-cover crop plots than in plots seeded with cereal rye (Figure 2B). Soybean height in plots with cereal rye cover were similar regardless of the seeding rate, and even in 2020 when the most cereal rye biomass was accumulated (Tables 2 and 3). Soybean plants in plots that lacked cereal rye cover were approximately 10.5 cm in height. The range of heights in cereal-rye-seeded plots was 12.2 to 12.9 cm. The increase in height is likely due in part to a soybean plant's need for sunlight and the necessity to grow above the cereal rye biomass to reach sunlight.

Soybean yield was lowest in plots that lacked cover (3,120 kg $ha^{-1}$), likely due to competition with weeds for limited resources (Van Acker et al. 1993). Yields were similar in plots that had cereal rye cover, regardless of seeding rate, and yield ranged from 3,420 kg $ha^{-1}$ to 3,660 kg $ha^{-1}$ (Figure 2C).

Interactions were observed between year and soybean stand and year and soybean yield (Table 2). Soybean stand and yield were both lowest in 2018 (Table 2). Soybean yields in 2019 and 2020 were similar to each other at 3,720 and 3,660 kg $ha^{-1}$, respectively. The differences observed are likely in part due to differences in stand count as well as total precipitation over the growing season. In 2018, when soybean yield was lowest, cumulative precipitation from May to September was 363 mm. Cumulative precipitation from May to September in 2019 and 2020 was 529 mm and 548 mm, respectively.

## Early-Season Waterhemp Emergence

Previous research indicated that cereal rye planted at 123 kg $ha^{-1}$ could suppress early-season waterhemp emergence (Cornelius and Bradley 2017; Whalen et al. 2019). In this study, waterhemp emergence varied substantially based on site and year as can be observed in the differences in waterhemp densities across the no cover plots (Table 4). In 2018, waterhemp emergence was delayed in all plots, including the no-cover plot 14 DAP (Table 4). However, sufficient waterhemp had emerged by 28 DAP to observe the effects of cereal rye seeding rate on waterhemp emergence. Waterhemp densities in plots that lacked cover were similar to densities in plots with cereal rye seeded at 34 kg $ha^{-1}$ (Table 4). All other cereal rye seeding rates resulted in lower waterhemp emergence compared to plots lacking cereal rye. By 48 DAP, similar cumulative waterhemp emergence was observed across all plots. The low densities of waterhemp at 14 DAP in 2018 were likely due in part to lower densities of weed seed in the soil seed bank at the 2018 site compared with 2019 and 2020 based on the total waterhemp emergence in the no-cover plots (Table 4). Precipitation also likely contributed to the delayed emergence. The spring of 2018 had 152 mm less precipitation than the 10-yr average (Table 1), whereas air temperatures were warmer than the 10-yr average.

In 2020, differences in waterhemp emergence were observed at 14, 28, and 42 DAP (Table 4). Densities were highest in no-cover plots with 240, 385, and 396 total emerged seedlings $m^{-2}$ at 14, 28,

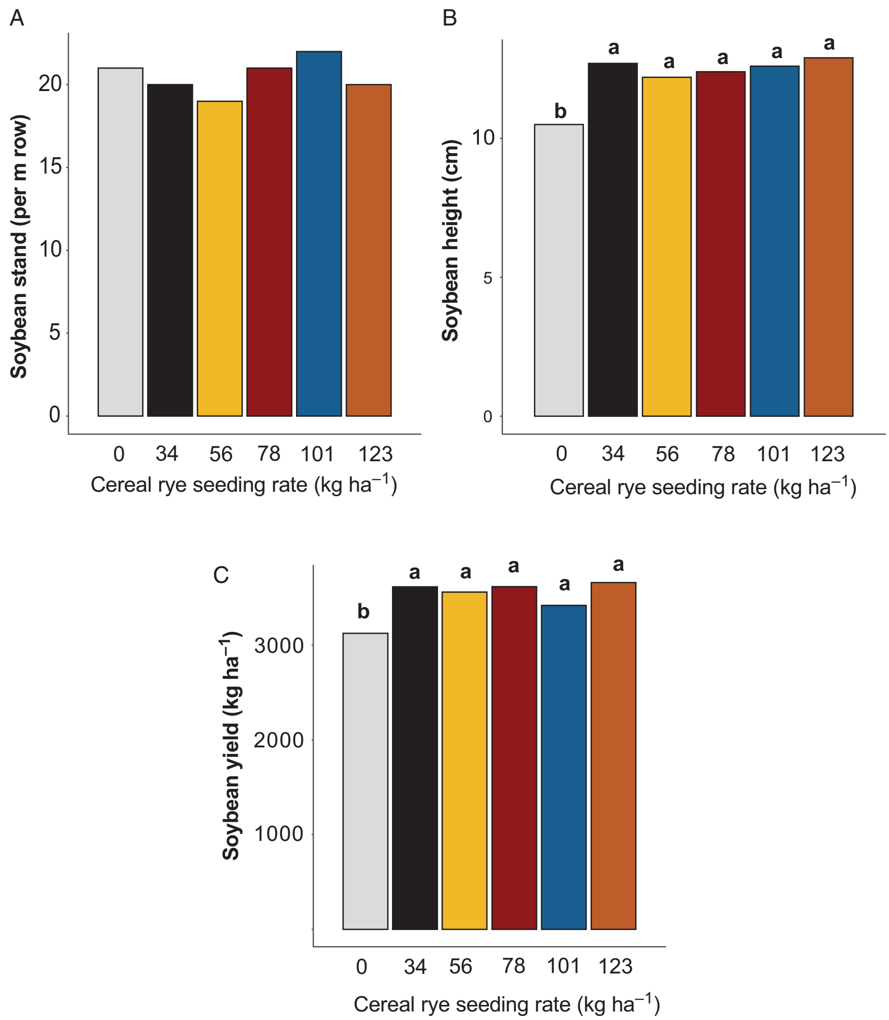


**Figure 2.** Influence of cereal rye seeding rates on soybean stand counts (A), soybean height (B), and soybean yield (C) 14 d after planting. Significance values were P = 0.27, <0.01, and <0.01, respectively. Data summarized across years (2018, 2019, 2020) in Columbia, MO.

and 42 DAP, respectively. Cereal rye seeding rates greater than 34 kg ha$^{-1}$ were most consistent in suppressing waterhemp emergence when compared to the no-cover plots at 28 DAP in 2018 and 14 DAP in 2020.

Waterhemp densities in 2019 were much higher than in 2018 or 2020, and there was no effect of cereal rye cover crop on waterhemp emergence (Table 4). These results from 2019 are not the first documentation of a lack of cereal rye effect on waterhemp emergence (Anderson 2014). In a study in Iowa, waterhemp was seeded at a rate of 5,500 per 0.25 m$^{-2}$ over cereal rye seeded at different rates and dates. Total waterhemp emergence was similar between treatments that had 0% cereal rye ground cover and 72% cereal rye ground cover (Anderson 2014). Accumulated cereal rye biomass in that study was much less than in our study; however, waterhemp densities were more comparable with approximately 6% of the 5,500 seed per 0.25 m$^{-2}$ germinating. In this current study, the number of weed seeds that emerged in 2019 when compared with 2018 and 2020 is likely due to the higher number of waterhemp plants that produced seeds in the previous fall. Collectively, the differences observed between site-years in this study underscore the importance of considering the soil weed seed bank. There may be a threshold of waterhemp seed density for which cereal rye biomass cannot compensate.

Visual ratings of waterhemp suppression were recorded 28 DAP each year (Table 5). Unlike the weed counts, which were cumulative and conducted in small areas within the plots, the visual ratings considered the entire plots and served as an evaluation of emergence between 14 and 28 DAP given that waterhemp were treated with glufosinate following the 14 DAP counts. An interaction was observed between seeding rate and year (Table 5). In general, higher seeding rates corresponded with higher control of waterhemp. However, visual ratings were much lower in 2019 and likely due to the density of waterhemp present.

To identify relationships between cumulative waterhemp emergence and cereal rye, linear regression models were generated. The best-fit models were generated with all years combined as well as for the 2020 data alone, because cereal rye had the most effect on waterhemp emergence in that year (Table 4). Models for the effects of cereal rye biomass, stand count, and height on waterhemp emergence are presented in Table 6. When all years are combined, the relationships were significant; however, the $R^2$ values were low. For each unit increase in cereal rye biomass, stand, or height there was a one unit decrease in waterhemp density with $R^2$ values of 0.11, 0.14, and 0.04, respectively. When only the 2020 data were used, the relationships remained similar. As cereal rye biomass, stand, or height increased by one unit, waterhemp densities decreased

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**Table 3.** Effects of cereal rye seeding rate and year on soybean height 14 d after soybean planting.

| Seeding rate | Soybean height 14 DAP[a] 2018[b] | 2019 | 2020 |
|---|---|---|---|
| kg ha$^{-1}$ | cm | | |
| 0 | 8.9 e | 11.9 a-d | 10.8 d |
| 34 | 12.4 a-c | 13.1 ab | 12.5 a-c |
| 56 | 11.9 b-d | 13.3 a | 11.9 b-d |
| 78 | 12.5 a-c | 11.7 cd | 12.9 a-c |
| 101 | 12.5 a-c | 12.6 a-c | 12.6 a-c |
| 123 | 13.2 ab | 12.9 a-c | 12.5 a-c |
| P-value | | <0.01 | |

[a]Abbreviation: DAP,days after planting.
[b]Means followed by the same letter are not significantly different.

**Table 4.** Effects of cereal rye seeding rates and year on cumulative waterhemp emergence 14, 28, and 42 d after planting.

| | 14 DAP[a] | | | 28 DAP | | | 42 DAP | | |
|---|---|---|---|---|---|---|---|---|---|
| Seeding rate | 2018[b] | 2019 | 2020 | 2018 | 2019 | 2020 | 2018 | 2019 | 2020 |
| kg ha$^{-1}$ | plant m$^{-2}$ | | | | | | | | |
| 0 | 0 | 726 | 240 a | 39 a | 927 | 385 a | 54 | 982 | 396 a |
| 34 | 0 | 825 | 12 b | 21 ab | 1096 | 54 b | 48 | 1126 | 54 b |
| 56 | 1 | 961 | 2 c | 12 b | 1288 | 50 b | 47 | 1317 | 50 b |
| 78 | 0 | 769 | 3 bc | 6 b | 1055 | 63 b | 33 | 1105 | 63 b |
| 101 | 0 | 776 | 2 bc | 10 b | 1164 | 49 b | 34 | 1189 | 49 b |
| 123 | 0 | 979 | 1 c | 11 b | 1412 | 56 b | 42 | 1441 | 57 b |
| P-value | NS | NS | <0.01 | <0.01 | NS | <0.01 | NS | NS | <0.01 |

[a]Data is cumulative from 0 to 14 DAP; 0 to 28 DAP; and 0 to 42 DAP, respectively.
[b]Means within a column followed by the same letter are not significantly different.
[c]Abbreviation: DAP, days after planting.

**Table 5.** Effects of cereal rye seeding rate and year on waterhemp control 28 d after planting.

| Seeding rate | Waterhemp control 28 DAP[ac] 2018[b] | 2019 | 2020 |
|---|---|---|---|
| kg ha$^{-1}$ | % | | |
| 0 | 1.4 i | 1.5 i | 1.4 i |
| 34 | 38 e | 11 h | 83 b |
| 56 | 53 d | 15 gh | 86 ab |
| 78 | 55 d | 16 f-h | 89 ab |
| 101 | 59 d | 21 fg | 91 a |
| 123 | 70 c | 23 f | 87 ab |
| P-value | | <0.01 | |

[a]Data presented as percent suppression.
[b]Means followed by the same letter are not significantly different.
[c]Abbreviation: DAP, days after planting.

**Table 6.** Regression models describing the relationship between cereal rye biomass, stand count, and height at soybean planting and waterhemp emergence for 42 d after soybean planting.

| Year[a] | Independent variable | Regression model | $R^2$ | P-value |
|---|---|---|---|---|
| All years combined | Biomass | y=442 – 1x | 0.11 | <0.01 |
| | Stand count | y=482 – 1x | 0.14 | <0.01 |
| | Height | y=192 -1x | 0.04 | <0.01 |
| 2020 | Biomass | y=273 – 1x | 0.46 | <0.01 |
| | Stand count | y=284 – 1x | 0.47 | <0.01 |
| | Height | y=371 – 1x | 0.56 | <0.01 |

[a]Models developed using only 2018 data or 2019 data were not significant and omitted from the table for reader ease. Data from combined years is presented for comparison to the models generated in 2020.

by one unit. However, the $R^2$ values were much higher at 0.46, 0.47, and 0.56, respectively.

The regression analyses were limited in that there was no biomass to analyze between 0 and ˜15,000 kg ha$^{-1}$. The inverse linear relationship between cereal rye biomass and early-season waterhemp emergence is likely to strengthen in studies with a broader range of biomasses. The inverse relationship between cereal rye height and waterhemp densities and stand and waterhemp densities may exist due to the amount of soil surface area covered by taller plants or a more densely planted stand.

## Conclusions

Soybean in cereal rye plots were slightly taller 14 DAP compared with the no-cover controls, but no adverse effects on soybean stand or yield were identified in this study. Reductions in waterhemp emergence in this study were most consistent when cereal rye was planted at rates of 56 kg ha$^{-1}$ or higher compared with the no-cover plots. However, the ability of cereal rye to suppress waterhemp emergence varied by year. Cereal rye did not affect waterhemp emergence in 2019 when waterhemp densities were greater than 700 plants m$^{-2}$.

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Collectively, these findings suggest that Missouri producers who plant cereal rye for early-season summer weed suppression should consider using seeding rates of 56 kg ha$^{-1}$ or higher to maximize the effects of cereal rye biomass on early-season waterhemp suppression. Producers should also have knowledge of the weed seedbank in a field and recognize that fall-seeded cereal rye is not a stand-alone weed control tactic. Recognizing these points are essential for successful use of cereal rye as one tactic in an integrated weed management approach.

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